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Research of an Innovative Mixer with Reduced Hydrodynamic Resistance

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ABSTRACT

The paper presents the results of research on a patented, new mixer design with a large blade pitch ($p/D \geq 2$) operating in a double-sided open diffuser positioned eccentrically in a water tank for various conditions. Mixing was carried out in the turbulent range ($Re > 10000$). Due to the bidirectional way of feeding the mixer located in the diffuser and the bidirectional way of leaving the diffuser by the mixed liquid, it is possible to generate wandering vortices, by which the mixing power of proposed design is greater than that of conventional impellers. The employment of the diffuser minimize the energy consumption of the design. The research analyzed the time of dissolving a dose of salt as a function of the rotational speed of the mixer and its three-stage position relative to the bottom. The study also examined the mixing power calculated from the current mixer rotational speed and the measured torque on the mixer shaft. The hydrodynamics of the mixing process were investigated using flow followers. Based on dissolution time and calculation, the system efficiencies for all condition are depicted. Investigation was conducted for mixer impellers with four different blade pitches. Finally, the impeller of the most advantageous pitch and position was determined.

Keywords: mixing, innovative mixer, screw impeller

INTRODUCTION

Mechanical mixing of single and multiphase liquid systems (suspensions, emulsions) with not very high viscosity is widely used in industrial processes. The mixing system consists of a tank and an impeller driven by a motor. The impeller transfers energy to the liquid to be mixed while inducing circulation (flow). The rotating impeller primarily induces a circular (circumferential) movement of the liquid. In addition, depending on the design of the impeller, it induces radial (Fig. 1a) or axial (Fig. 1b) movement. Radial flow is generated by impellers with blades perpendicular to the direction of rotation of the mixer, i.e. the blade angle is $\alpha = 90°$. Examples of such mixers are disc-turbine (Rushton RT turbine) and flat-blade turbine impellers. The inclination of the blades, i.e. the reduction of the blades angle ($\alpha < 90°$), results in axial fluid flow. Examples of such impellers are pitched blade turbines (PBT) and propellers (PR).

Axial flow is also produced by the screw impeller, especially when operating in a tube diffuser. It demonstrates a high intensity of circulation for high-viscosity liquids [1], and in the case of low-viscosity fluids in the turbulent mixing range, it also works effectively [2]. Experimental studies and numerical simulations indicate that in the case of high-viscosity liquids, pitch $p/D \approx 1.5$ (where: p- pitch of the impeller

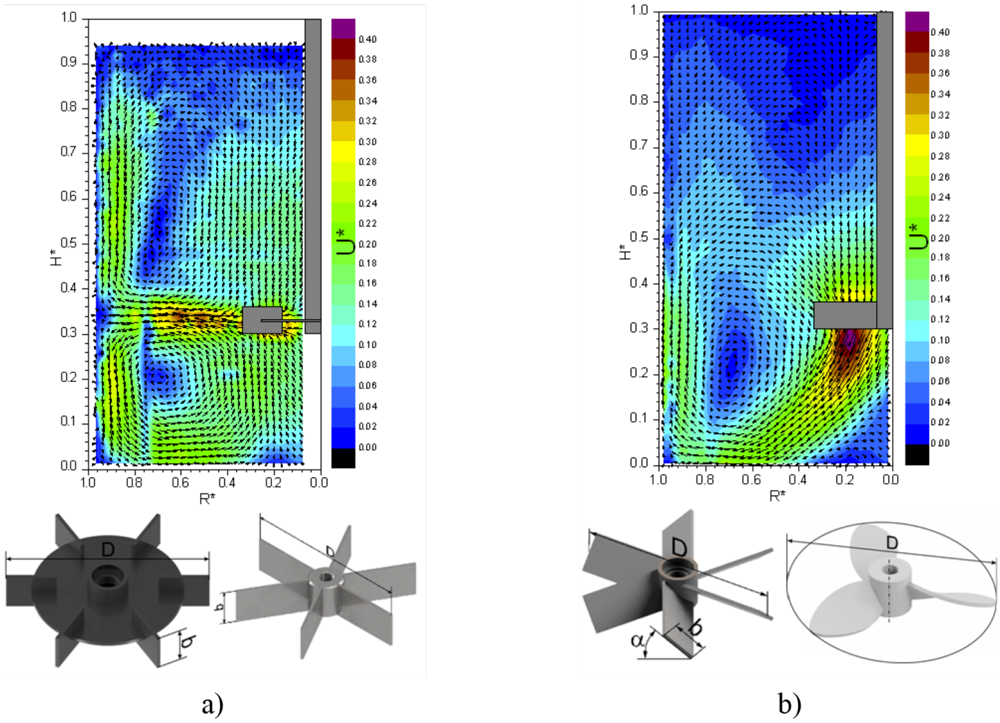


Figure 1. Methods of liquid circulation in a mixer and the impellers that generate them: (a) radial-circumferential, (b) axial- circumferential

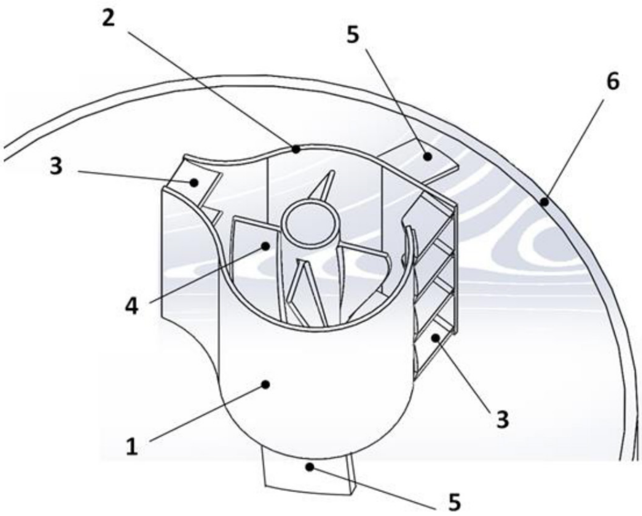


Figure 2. Screw impeller in a diffuser: 1, 2 – diffuser side surfaces, 3 – stream deflectors, 4 –screw impeller, 5 – supports, 6 – tank wall

blade [m], D- diameter of impeller [m]) provides the greatest efficiency [3]. However, in the context of laminar mixing, impellers with diameters larger than 1/3 of the T-tank diameter are often used [4, 5, 6].

For mixing liquids with low viscosities, a novel diffuser design with partially open side surfaces (Fig. 2) was developed and patented [7]. The impeller generates an axial flow directed downwards or upwards, depending on the direction of rotation (or coil direction) of the impeller 4. At the same time, the rotating impeller of the mixer 4 causes – due to the side openings 3 – a transverse flow through a diffuser composed of two elements 1 and 2 of different shapes. The side openings of the diffuser can accommodate stream deflectors or static impellers. Supports 5 fix the diffuser to the wall of the tank 6 and allow it to be rotated to vary the angle between the outflow stream and the tank wall.

In the described design, impellers with different blade pitches can be used, whereby the flow of liquid flowing axially through the diffuser can be varied. On the other hand, the use of diaphragms at the side inlet of the diffuser enables the change of the transverse stream flowing through the mixer. When bio-suspensions are mixed, the axial flow should be directed downwards. At the bottom of the tank, this stream flows radially and should be directed upwards on the opposite side of the mixer. During the upward flow, it crosses with the circumferential flow [8]. This should intensify mixing, but with relatively low shear stresses that will not destroy the microorganisms [9]. The impeller can be mounted at various depths of the tank so that the mixing of the liquid streams is most intense and no ‘dead zones’ are formed near the bottom with no liquid flow. Tests carried out for a similar mixer (differing in the shape of the diffuser) demonstrated the complex form of liquid flow in the tank which is shown schematically in Fig. 3.

As might be guessed, there is no universal mixer ‘for everything’. Axial-flow impellers are typically used for slurries, while radial-flow mixers are used in aerated (gassed) systems. For many years, the Rushton turbine (RT) with a diameter D close to 1/3 of the diameter of the tank T was the optimal design for mixing liquids in fermenters [10]. This type of impeller generates

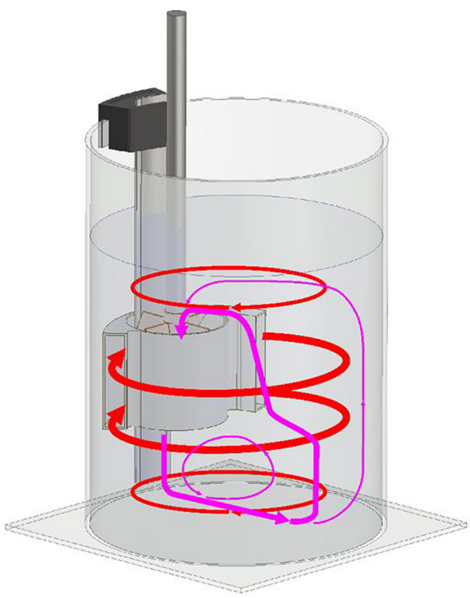


Figure 3. Liquid flow for an eccentric screw impeller in a side-flow diffuser

intense turbulence in the proximity of the impeller [11–13], and therefore disperses the gas well and disintegrates the bubbles. However, mixing in the remaining volume of the fermenter is much worse (weaker) and can lead to heterogeneity in the pH or oxygen distribution [14–16]. The positioning of the blades perpendicular to the direction of movement causes high shear stresses in their proximity leading to a strong disintegration of the microorganism cells [17]. The blades set up in this manner create a high resistance which is the reason for the massive power consumption. For the six-blade impeller (FBT), the power number defined as

$$Eu = \frac{P}{N^3 \cdot D^5 \cdot \rho} \tag{1}$$

where: *Eu*- power number [-], *P*- mixing power [W], *N*- rotational frequency [s^{-1}], ρ- density [kg/m^3]

in the turbulent mixing range

$$Re = \frac{N \cdot D^2 \cdot \rho}{\eta} \tag{2}$$

where: *Re* – Reynolds number for the mixing process [-], η – dynamic viscosity [Pa·s]

with installed tank baffles, reaches the value of Eu = 4 ÷ 4.4, and for RT it is even higher and comes to Eu = 5 ÷ 6 [18]. In this respect, axial flow impellers are less energy-intensive, because for a six-blade PBT impeller with an inclination angle of 45° Eu ≈1.6 [19, 20] and for the three-blade propeller (p/D = 1) Eu ≈ 0.34. Nonetheless, the mixing efficiency is determined by the work

$$W = \tau_m \cdot P \tag{3}$$

where: *W* – work [J], τ_m – mixing time (homogenization) [s]

done to achieve the required degree of mixing (technological effect). From two impellers being compared, the more appropriate will be the one which will achieve the required homogenization (mixing) time τ_m with a lower energy outlay determined as $\tau_m \cdot P$. For a given geometric system, the dimensionless homogenization time is described by the equation:

$$\tau_m \cdot N = C_1 \cdot Re^b = const \tag{4}$$

where: C_1- coefficient [-].

Due to the limited data on the detailed form of the equation (4), comparison of mixing times for different types of impellers is difficult. However, the efficiency of the process can be determined [20]

$$U_E = \frac{\tau_m \cdot P}{V} \tag{5}$$

where: U_e – efficiency [J/m^3], V- volume of liquid in the mixer [m^3]

by the work done per unit volume of mixed liquid to achieve the intended technological effect. Literature data [1] indicate that the mixing time τ_m is proportional to the primary circulation time τ_c

$$\tau_m = C_2 \cdot \tau_c = C_2 \cdot \frac{V}{V_p} \tag{6}$$

where: C_2 – coefficient [-], τ_c – circulation time [s].

The value of the coefficient $C_2 = 4 \div 5$, i.e. four or five times recirculation of the liquid is needed to achieve the mixed state [1]. Interestingly, for a screw impeller with a diffuser, this condition is also met when mixing highly viscous liquids [5]. To use formula (6) it is necessary to know the pumping capacity of the impeller, and information in this area is also limited, as it is determined experimentally from velocity profiles. Nonetheless, a reduction in homogenization time should give measurable energy benefits. However, there are limitations in this respect too. Experimentally, it has been found that the boundary (shortest) homogenization times are [1]

$$\tau_m \geq 10^{-4} \cdot \frac{T^2 \cdot \rho}{\eta} \tag{7}$$

For example, for a tank $T = H = 2$ m and liquid with the parameters ρ = 1000 kg/m^3 and $\eta = 1$ mPa·s, $\tau_m \geq 400$ s is obtained. Thus, in such a tank, no impeller can mix the system faster than in $\tau_m \geq 6{,}7$ min.

According to equation (3), the reduction of energy input W can be achieved by reducing the mixing power P. This could be done by design improvements of existing impellers or developing of new ones. For example, the use of an airfoil in the blade cross-section allows the mixing power to be reduced by several percent [21] while the hydrodynamics remain unchanged. Reducing the homogenization time can be achieved by increasing turbulence in the mixed liquid, e.g. by introducing fixed baffles. However, this usually increases the mixing power, but does not create a funnel beside the mixer shaft. The non-funnel effect also can be achieved by eccentric placement of the impeller in the tank without baffles [10].

Literature data [22] indicate a significant influence of the distance of the impeller from the bottom in the case of agitators generating radial-circular flow (Rushton turbine, flat blade turbine). In contrast, for impellers with strong axial flow (pitched blade turbine, propeller), the relationship is much smaller. Also, the effect of impeller pitch on mixing power is significant for turbulent flows. Since, in the case of the design shown in Figure 2, the liquid flows out in two directions, it is not possible to simply determine the circulation time. It is also difficult to determine the location of the conductivity probe to specify the homogenization time. Yet, since the presented impeller is to be used for mixing bio-suspensions [23], instead of the homogenization time, the dissolution time of a specific mass of salt can be investigated.

A certain analogy to mixing with an innovative mixer can be found in cylindrical surfaces partially immersed in the mixed fluid, which are used to impart chaotic motion to the fluid [24]. This takes place between the diffuser and the mixer at the inlet and outlet of the diffuser, where the fluid direction changes in an unsteady manner. The design of proposed mixer is novel and thus characteristics of power (Eu = f(Re)) and mixing intensity are not yet determined. Therefore, the aim of this study is to define power consumption of the mixer and dissolution times for different mixing system conditions (blade pitch and position of the impeller). Outcomes of the research will enable to elaborate the configuration that provides the best efficiency of the mixing system.

After successful preliminary tests another direction of research could be the effects of scale or multiphase of mixed fluids [25] or employment of the proposed mixer for non-Newtonian fluids [26]. It will be important to continue research work on other substances, e.g. those subject to aggregation [27].

METHODOLOGY AND RESEARCH

The tests were carried out in a flat-bottomed tank with a diameter of T = 292 mm (Fig 4). The tank was filled with water (t = 20°C) to a height of H = 340 mm. The propoulsion system drive the shaft in range of rotational frequency from 200 min^{-1} to 600 min^{-1}. Integrated sensors system measures rotational frequency with accuracy of 1 min^{-1} and generated torque with accuracy of $0{,}1 \cdot 10^{-3}$ Nm. All gathered date were

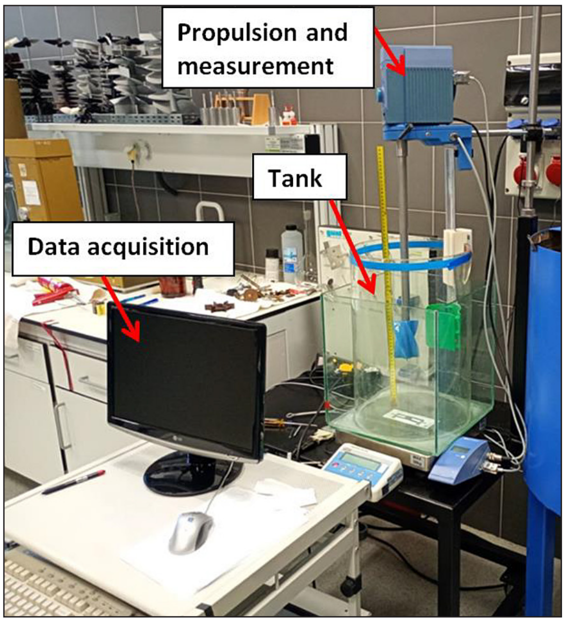
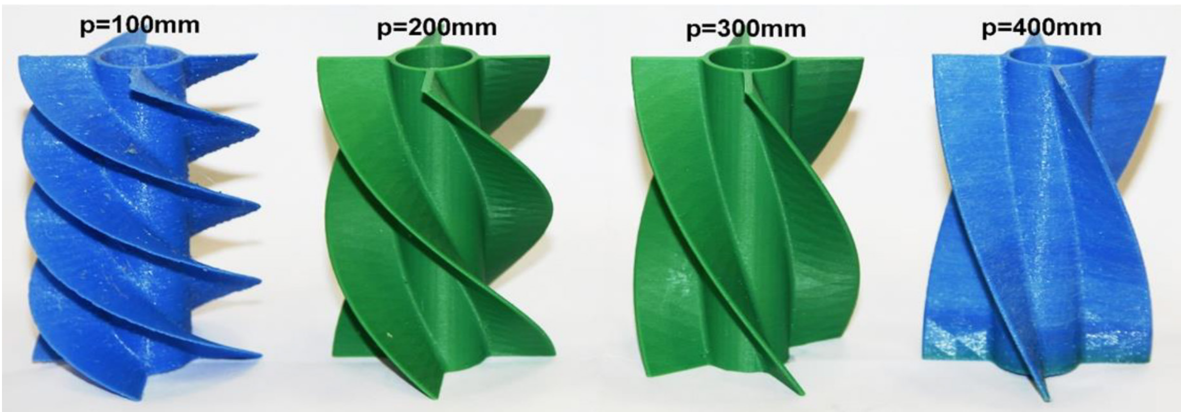


Figure 4. Photo of the test stand

registered on a hardware of computer. Four impellers were subjected for investigation, shown in Figure 5, with a diameter of D = 65 mm and different blade pitches = 100, 200, 300 and 400 mm. A small pitch of the blades should produce a larger axial flow, while with larger pitches the mixer should generate a larger circumferential flow. The distance of the centre of the height of the impeller H_z from the bottom was: 0,250·H, 0,375·H, 0,500·H, 0,625·H, 0,750·H (impeller suspension heights). The distance between the shaft axis and the tank axis was e = 83 mm. Tests were carried out for cases without and with a diffuser. The impellers were driven by an IKA EURO-ST P CV system controlled by Labworldsoft 4.6. Such configuration of the test stand enables to investigate:

- hydrodynamics of the mixer – in order to illustrate the flow of the liquid in the stirred vessel, flow followers with a diameter of 3.2 mm were used [28]. The movement of the flow followers at rotational frequencies N = 200, 300, 400, 500 and 600 min^{-1} was recorded with a Canon EOS 5D Mk II camera using strobe lighting. The Meike Speedlite MK320 lamp mounted above the free surface of the liquid generated 10 flashes with a frequency of 10 Hz. The impeller suspension heights were the same as during the mixing power measurements (see conditions above Fig. 5).
- mixing power – the torque M measurements were carried out in the rotational frequency range from N = 50 min^{-1} to N = 600 min^{-1}, which corresponds to the range of Reynolds numbers from Re = 3520 to Re = 42250. The measurement frequency of the rotational frequency N and torque M was 1 Hz. Based on measured values, mixing power P was calculated as: $P = 2 \cdot \pi \cdot N \cdot M$.
- dissolution time – the dissolution time was determined for 25 g NaCl. The salt was poured into the tank and the impeller was started, and next the time measured. Measurements were made for rotation frequencies N = 200, 250, 300, 350, 400, 450, 500, 550 and 600 min^{-1} and impeller suspension height H_z = 0,25·H, 0,5·H i 0,75·H. Two measurements were taken for each setting.
- system efficiency – based on dissolution time and formula (5) the system efficiencies for all conditions were calculated and depicted.



R2 p/D = 1,54 R3 p/D = 3,08 R1 p/D = 4,62 R4 p/D = 6,15

Figure 5. Investigated mixer impellers with different blade pitches

RESEARCH AND DISCUSSION

Hydrodynamics

The high positioning of the impeller ($H_z = 6/8 \cdot H = 255$ mm) results in air being drawn through the funnel when the limiting rotational frequency is exceeded. In the case of impeller R2 (pitch p = 100 mm) this occurs at a rotational frequency of 400 min^{-1} < N < 500 min^{-1} (28165 <Re < 35210). For the other impellers: R3 (p = 200 mm) – 300 min^{-1} < N < 400 min^{-1} (21125 <Re < 28165), R1 (p = 300 mm) – 200 min^{-1} < N < 300 min^{-1} (14080 <Re < 21125), R4 (p = 400 mm) – 200 min^{-1} < N < 300 min^{-1} (14080 <Re < 21125). Thus, increasing the pitch of the impeller blades results in earlier intake of gas. This is due to the stronger circumferential flow of the liquid, which results in a funnel being formed at the mixer shaft. In turn, all followers were lifted from the bottom of the tank at rotational frequencies: R2 – N > 500 min^{-1} (Re > 35210), R3 – N > 400 min^{-1} (Re > 28165), R1 – N > 500 min^{-1} (Re > 35210), R4 – N > 500 min^{-1} (Re > 35210). In the case of impellers R1 and R4, this is due to the disturbance of the liquid circulation by air bubbles. The image of the mixer interior for the discussed impeller suspension height and rotational frequency N = 500 min^{-1} is shown in Fig. 6.

Many biotechnological processes use aeration to supply oxygen to the biomass. However, in the case of self-aeration, the airflow dispersed in the liquid depends on the mixing frequency [29, 30, 31]. Thus, the adjustment of the air flow is limited, and affects the intensity of the mixing. If the aim of the process is mixing without aeration, a high placement of the mixer is not a good solution.

The low positioning of the impeller ($H_z = 2/8 \cdot H = 85$ mm) results in all flow followers - irrespective of blade pitch - being lifted off the bottom at rotational frequencies N > 300 min^{-1}. This is most likely caused by the fact that the axial stream of liquid flowing out of the diffuser on reaching the bottom must change direction and entrains the flow followers with it. On the other hand, when the impeller is placed low, turbulence in the upper part of the tank is reduced (extended paths of flow followers). However, in the case of impellers with a larger pitch, at higher rotational frequencies (N > 500 min^{-1}, Re > 42250) a formed sucking air from above the free surface (Fig. 7 for R3 and R4).

At positions H_z = 127,5 mm ($H_z = 3/8 \cdot H$), H_z = 170 mm ($H_z = 4/8 \cdot H$) and H_z = 212,5 mm ($H_z = 5/8 \cdot H$) no gas aspiration was observed from above the interfacial surface (Fig. 8).

More detailed information on the hydrodynamics in the tank with the tested impellers requires further research, e.g. using the PIV system or computer simulation e.g. introduced in [32] and [33].

Mixing power

Within the turbulent mixing range, the mixing power number should have a fixed value. According to the definition of the power number, torque M on the mixer shaft should be proportional to the square of the rotational frequency N. If the mixing power is reduced during aeration, the deviation of the measuring points from the theoretical line should be visible. Examples of formulas for impeller R4 are shown in Figure 9.

In the case of high impeller placement (H_z = 255 mm), no significant deviation of the measurement points from curve $M = C \cdot N^2$ can be seen. This means that the presence of the gas phase does not affect the flow resistance of the impeller blades. Based on the recorded measurement data, graphic correlations $Eu = f(Re)$ were prepared. Figure 10 shows such a correlation for the suspension height H_z = 170 mm.

According to the literature data in the field of turbulent mixing, the power number is constant Eu = const. The dispersion of the measurement points results from the dynamic unbalance of the shaft and the impeller, but due to the large number of measurement points, the obtained average value can be considered reliable. The average values of the number of mixing powers are shown in Figure 11. Based on the analysis, it can be stated that:

- the use of a diffuser reduces the mixing power – this is most likely due to the direction of the liquid flow and the reduction of turbulence around the impeller,
- power reduction during gas aspiration is very small,
- increasing the pitch of the blades increases the mixing power – increasing the pitch (more vertical setting of the blades) increases the resistance during the movement of the blades,
- the effect of the height of the impeller suspension on the mixing power is small (except for the case of R4 without a diffuser) – generally

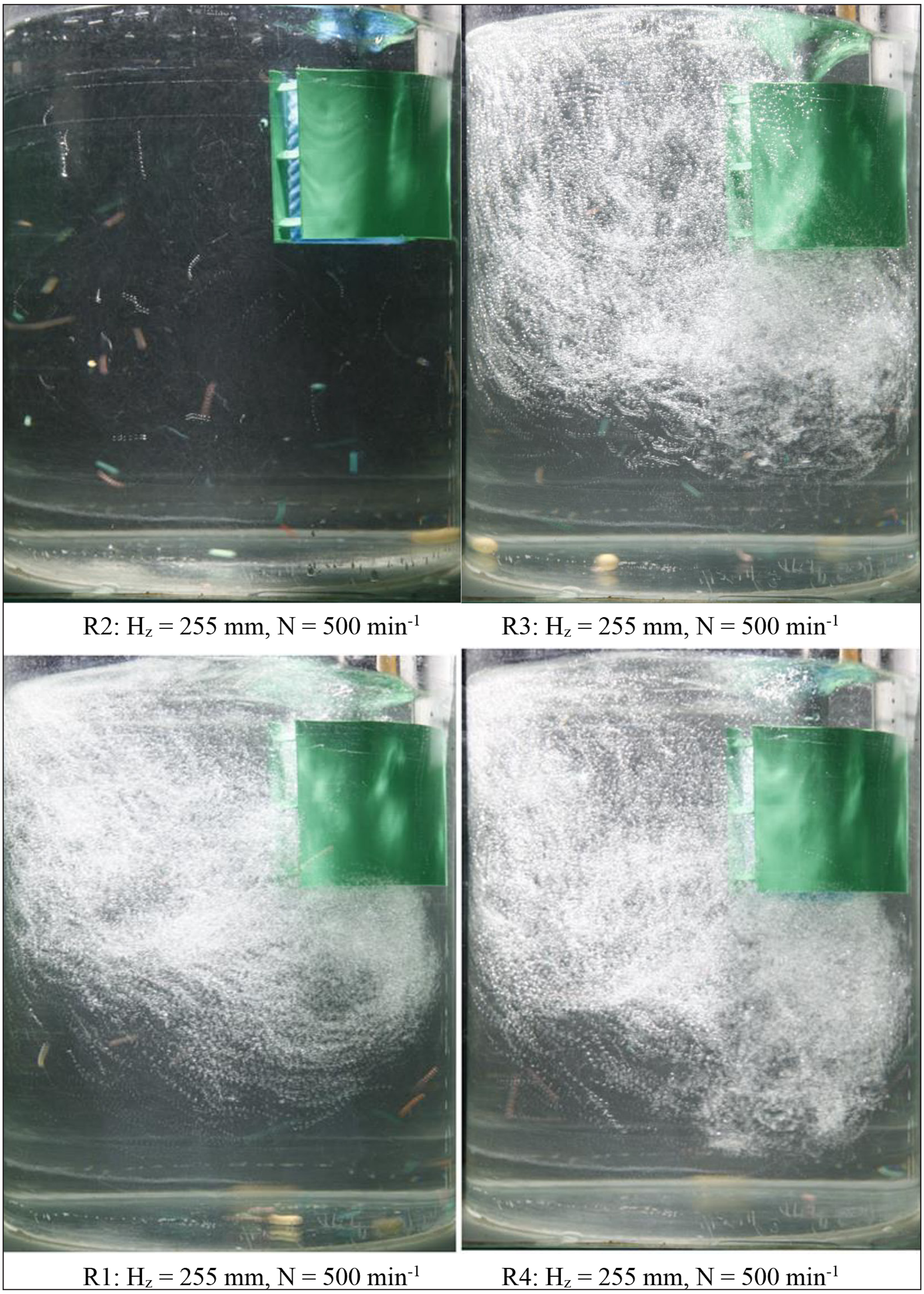


Figure 6. Trajectories of flow followers for high impeller placement

lower impeller placement results in a very small reduction in power.

The average values of the number of powers for the impellers are listed in Table 1. Literature data [1, 2] for an impeller with pitch p/D = 1.5 in the diffuser and Reynolds number Re = 10000 give the value Eu = 1.1, and for p/D = 2.0 Eu = 1.5. These values are lower than those obtained in the tests, but the difference may be due to the off-centre placement of the impeller and differences in liquid flow resulting from side outflow. However, the tendency of increasing mixing power with increasing blade pitch is maintained. No literature data can be found about the mixing power of screw impellers for p/D > 2. Compared to conventional agitators,

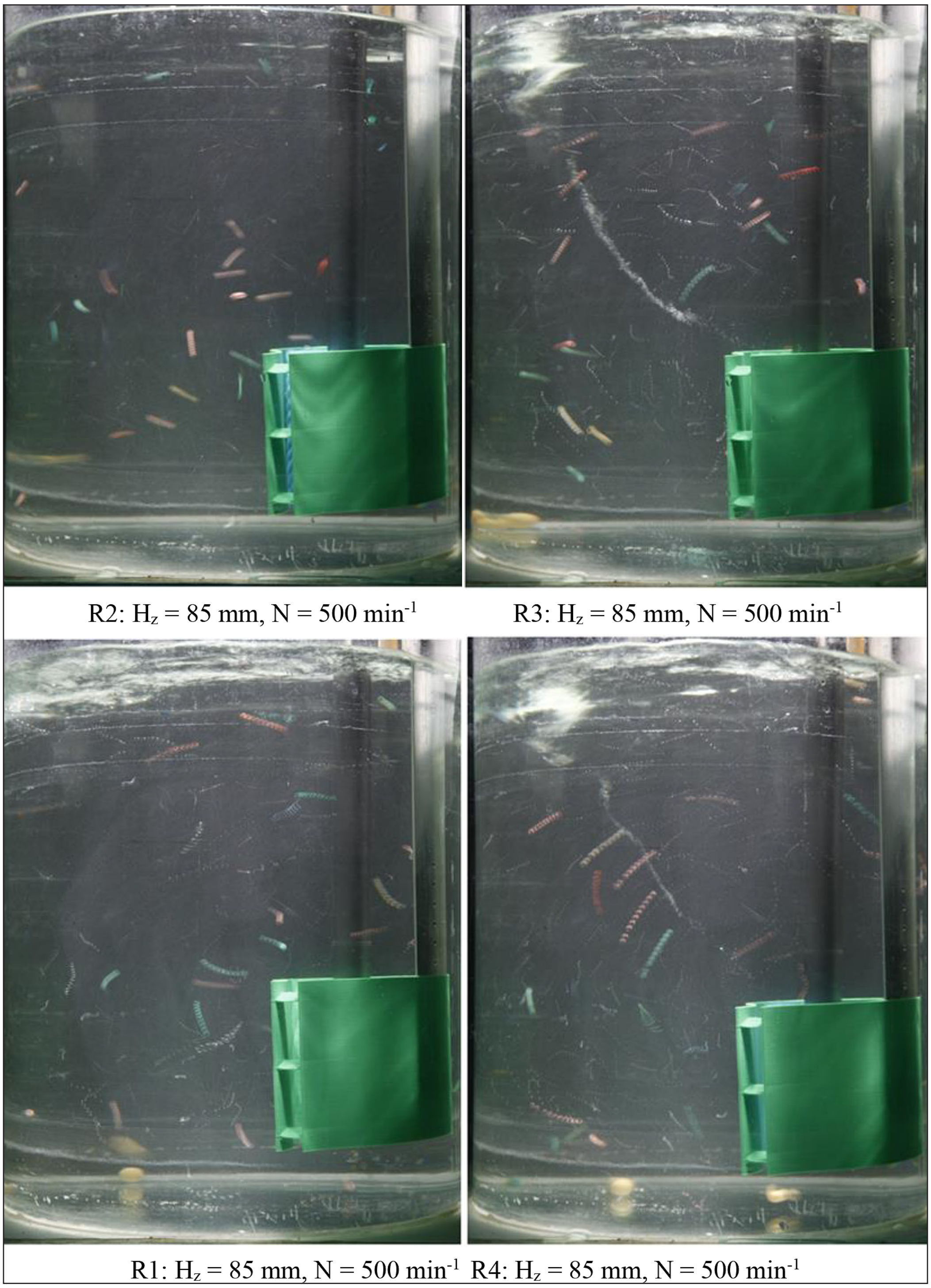


Figure 7. Trajectories of flow followers for low impeller placement

the power numbers of the investigated impeller are large. For the RT impeller, the literature provides values from *Po* = 5 to *Po* = 6, and for FBT *Po* = 4.4 [34]. This is most likely due to the large surface area of the blades, much larger than that of the RT and FBT impellers. Even greater differences occur with regard to mixers generating axial flow. For a mixer with six blades inclined at an angle of 45°, Eu = 1.6, and for a three-blade propeller mixer with a pitch, p = D Eu = 0.35. However, to assess the operation of the mixers, the energy consumption needed to achieve the required degree of mixing (homogenization) should be considered, as determined by the relationship (5). In greater systems, the differences of energy consumptions in dependence of employed mixer design are much more significant [35]. The gas flow rate through the high-mounted impeller – contrary to literature suggestions [29]

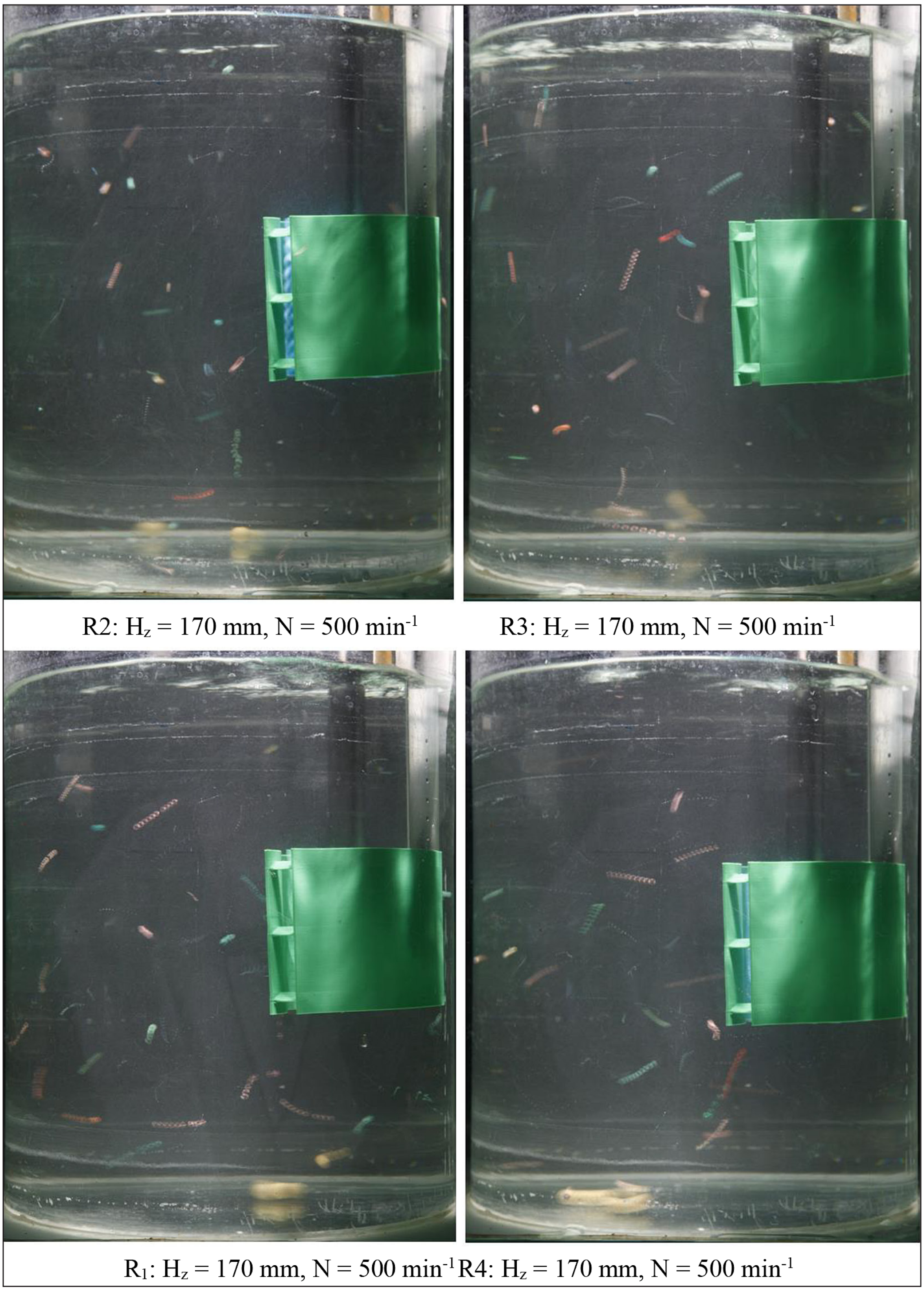


Figure 8. Trajectories of flow followers for central impeller placement

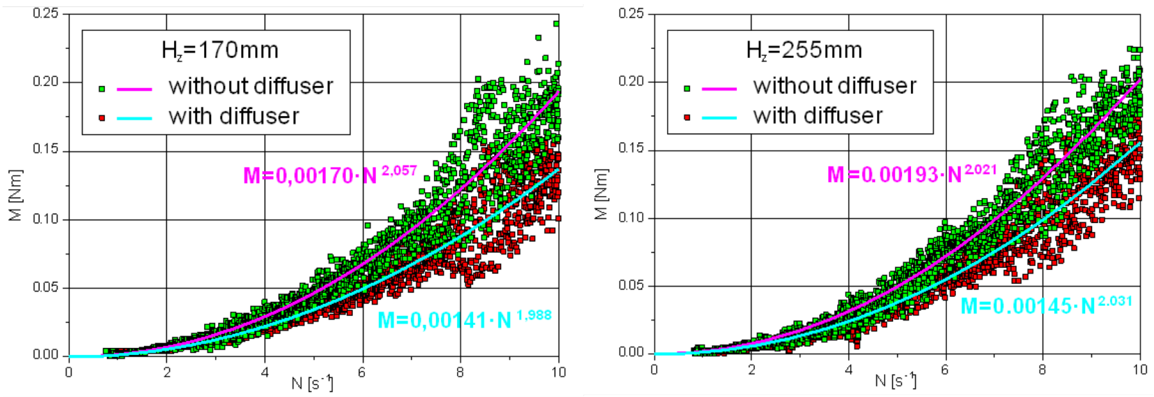
– does not reduce the mixing power. It is probably small enough not to affect the resistance to blade movement in the liquid-gas system.

Dissolution time

Figure 12 shows the average dimensionless dissolution times, i.e. the products of the measured dissolution times and $N \cdot t$. This corresponds to the number of rotations of the mixer impeller required to completely dissolve the salt sample.

Based on the Figure 12, it can be stated that for the process of salt dissolution in the tested system:

- the dissolution times depend on the height of the impeller placement; the longest was found for the position in the middle of the liquid height in the tank, while for the low and upper placements the dissolution times are similar,



R4: Hz = 170 mm R4: Hz = 255 mm

Figure 9. Dependence *of* $M = f(N)$

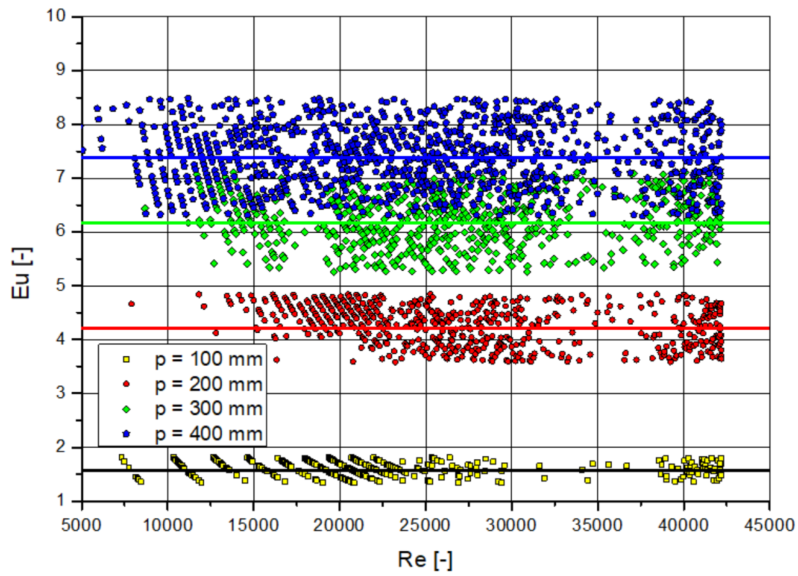


Figure 10. Correlation $Eu = f(Re)$ for height $H_z = 170$ mm ($H_z = 4/8 \cdot H$)

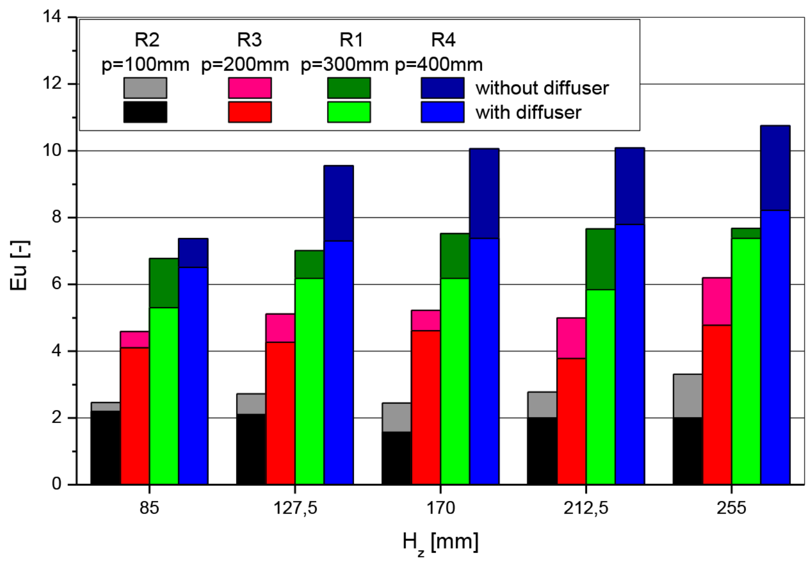


Figure 11. Power numbers of the tested impellers for turbulent mixing

Table 1. Power numbers for individual impellers

Sample	*Eu [-]*			
	R2	R3	R1	R4
Without diffuser	2.74	5.22	7.33	9.56
With diffuser	1.97	4.31	6.18	7.44

- in the range of pitches from p = 100 to p = 300 mm, extending the pitch of the blade shortens the dissolution time, but further increasing the pitch does not result in any changes,
- in the Reynolds number range from Re = 20000 to Re = 30000, the dissolution times reach maximum values and shorten for higher Reynolds number values, with the maxima being more pronounced for longer pitches,
- the shortest dissolution times occur for impeller R1 with pitch p = 300 mm – in this case the impact of the impeller placement height is smallest,
- the dimensionless dissolution times depend on the Reynolds number, but in most cases do not fulfil equation (4).

System efficiency

Figure 13 shows the efficiencies of the tested mixing systems calculated from formula (5) using dissolution time. The system with the smallest blade pitch (R2) shows the best efficiency irrespective of the mixer mounting. However, its efficiency decreases with increasing rotational frequency. For the larger blade pitch (R3) of the low and upper impeller placement, the efficiency for Re > 25000 is constant, but for the central impeller position it decreases significantly. Further increases in pitch are characterised by lower efficiencies (by about 25%), but constant for Re > 25000. The system with the largest blade pitch (R4) demonstrates the lowest efficiencies for Re > 30000. For higher Reynolds number values, efficiencies improve, but depend on the height of the impeller placement.

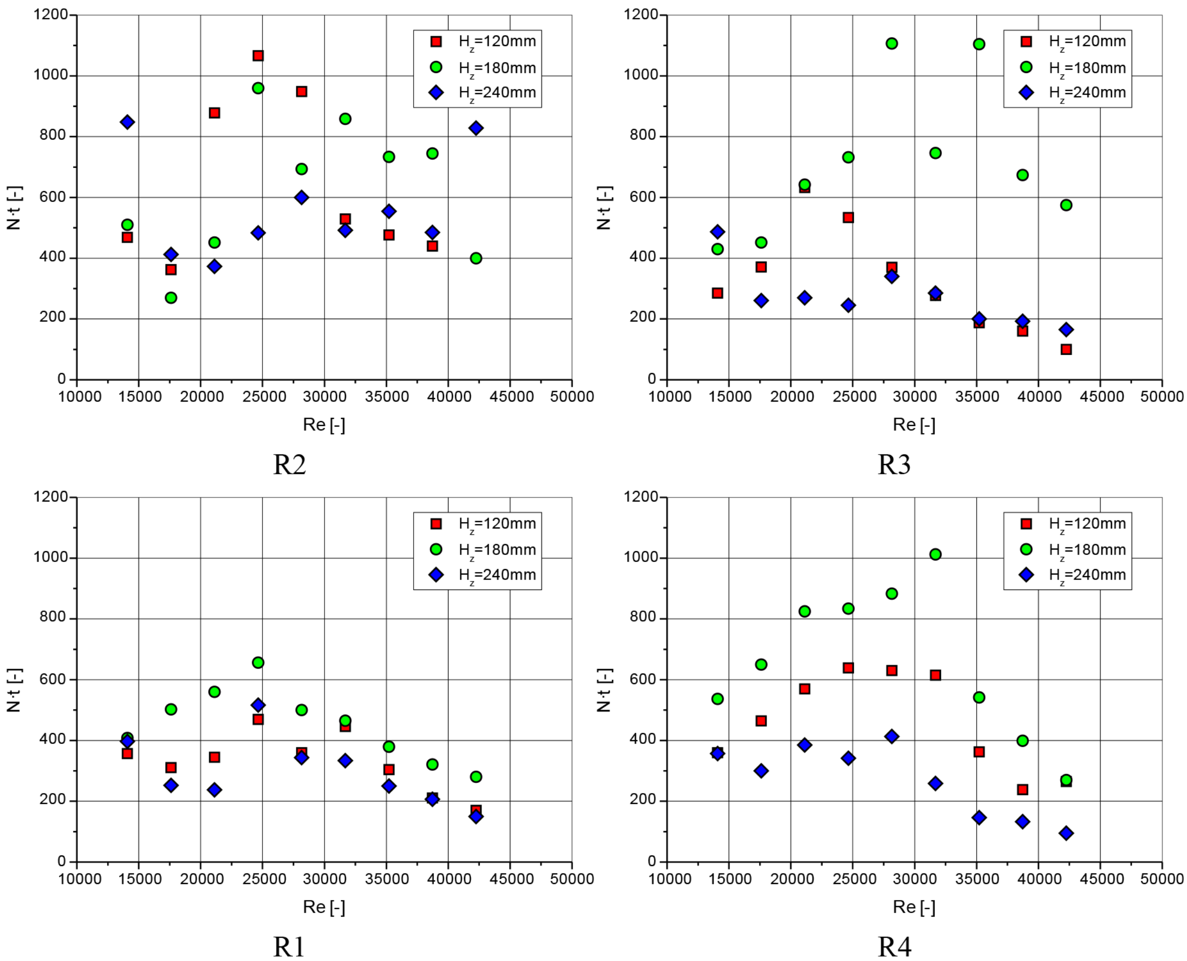


Figure 12. Dimensionless dissolution times

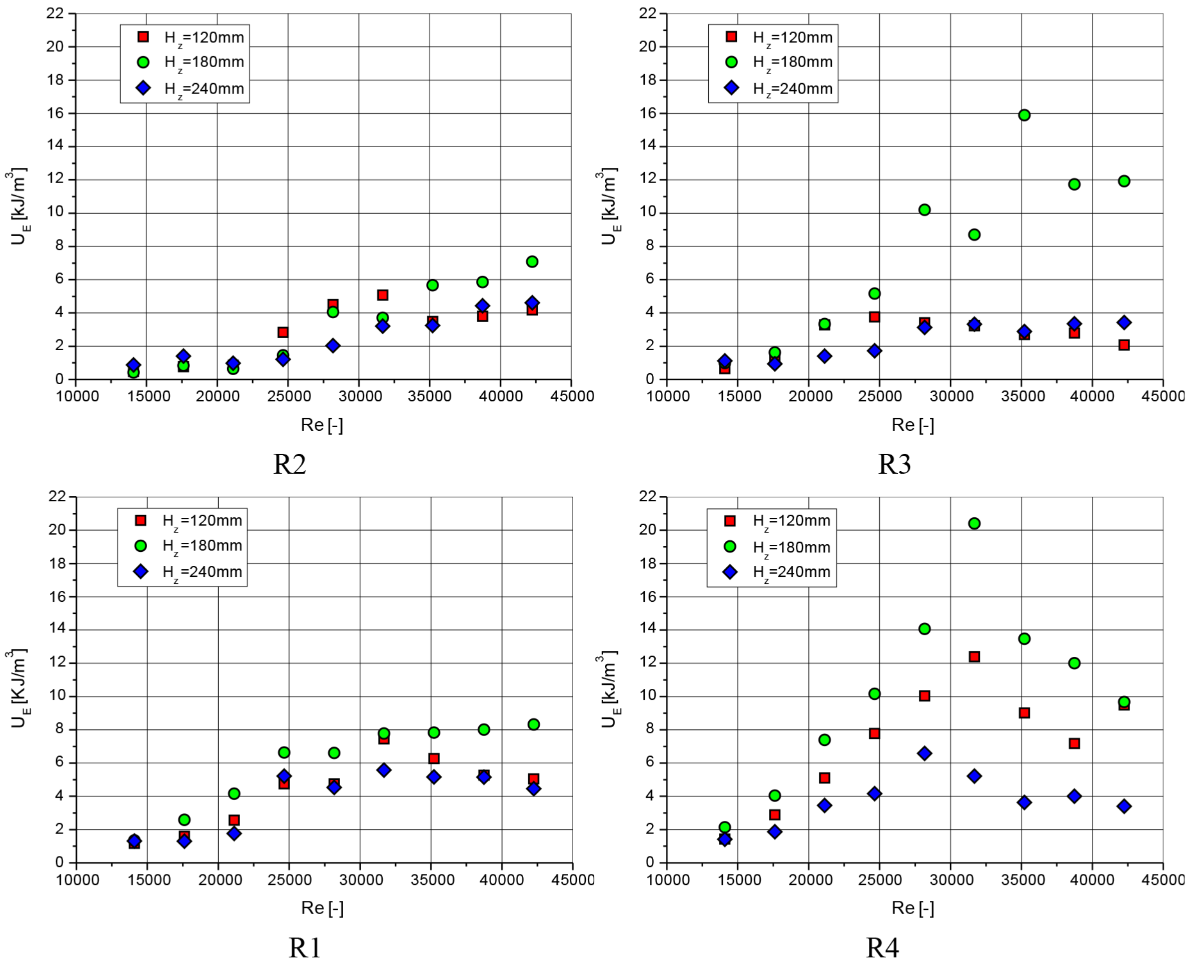


Figure 13. Efficiency of mixing systems

CONCLUSIONS

Introduction of additional liquid inflow and outflow surfaces during mixing has not been achieved so far in mixers without a diffuser. In order to additionally turbulate the liquid rotating in the tank, turbulent baffles were placed in the tank, which, attached to the tank walls, significantly increased the mixing power. The use of a diffuser was and is a big challenge because the number of geometric parameters that affect its operation is practically unlimited. The presented design is a compromise between technological possibilities and potential performance.

The proposed mixer, thanks to its construction and some separation from the main vortex occurring in the tank during the mixing process, makes it possible to use many mixers simultaneously in one tank. Thanks to the streamlined surfaces these mixers are not disturbing to each other but even cooperate and increase the energy of the central vortex in the tank.

The advantage of proposed mixer is the reduction of production costs and especially operating costs. This applies especially to large industrial installations requiring huge amounts of energy, where mixing processes, especially continuous ones, are an indispensable component.

From analysed conditions and efficiency point of view, the best design solution represents the impeller with a relative pitch of $p/D = 3.08$, and slightly poorer results are obtained by an impeller with a pitch of $p/D = 4.61$. Both design solutions provide the shortest mixing times for $Re > 25000$, with high mixing intensity.

Due to the possibility of sucking gas from above the liquid surface, placing the mixing system in the lower part of the tank ($H_z/T < 0,33$) is the best solution. However, if the impeller is lowered further, there may be an effect of inhibiting the axial flow through the bottom.

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